IEICE TRANS. ELECTRON,(JULY 2003),Vol.E86-C,No.7pp1245-1250

PAPER *Special Issue on Recent Progress in Microwave and Millimeter-wave Photonics Technologies*

Generation of 60 GHz Dual-Mode Optical BPSK Signal Pair for Crosstalk-Free QPSK Photodetection by Optical Modulation Scheme with Double RF Inputs and Suppressed Carrier Feature

Shinji NAKADAI[†], Kaoru HIGUMA[††], Satoshi OIKAWA[††], Masato KISHI[†]
and Masahiro TSUCHIYA[†a)], *Regular Members*

SUMMARY A novel optical modulation scheme is proposed for synthesizing a pair of dual-mode optical BPSK signals with an orthogonal phase relationship via a $LiNbO_3$ Mach-Zehnder modulator (MZM) with dual RF signal inputs and a carrier suppression feature, which enables the generation of a crosstalk-free QPSK signal at the photodetection stage. With this method, one can compensate the drawback, that is bandwidth broadening, in our previously proposed method where a dual-mode optical QPSK signal is generated on the basis of narrow-angle modulated QPSK signal injection into a double-sideband suppressed carrier MZM device. We have carried out experiments for 60 GHz performance demonstration of this QPSK signal generation mechanism, and the results indicate the effectiveness of the present scheme.

key words: RoF technique, optical millimeter-wave signal generation, dual-mode optical signal, QPSK modulation format, LN modulator

1 . Introduction

Fiber-optic transmission of radio-frequency or millimeter-wave (mm-wave) frequency signals is one of the technical issues studied most actively in the field of microwave photonics [l], [2]. In a conventional sense, the transparency feature is highly demanded at both ends of a fiber-optic link where the electrical-to-optical and optical-to-electrical conversion processes take place with little bandwidth limitation or nonlinear distortion being preferred. On the other hand, one can note that there exists another recent trend, where attractive functionality is brought about at the stage of electrical-to-optical conversion by the utilization of advanced optical modulation devices and their novel driving techniques. For example, it is possible to multiply an electrical carrier frequency by making use of nonlinear characteristics of a $LiNbO_3$ (LN) Mach-Zehnder modulator (MZM) [3], [4]. A driving method called double-sideband modulation with suppressed carrier (DSB-SC) [3] is the most representative and probably smartest methocl of providing such a useful functionality as frequency-doubling. Its dual optical mode property is, furthermore, advantageous for the efficient suppression of the dispersion-incluced power penalty problems.

One should note, however, that the nonlinearity eliminates some important modulator operations relying on device linearity. For instance, an RF signal in a phase-shift-keying (PSK) modulation format cannot be applied directly to the conventional DSB-SC scheme. This is rather troublesome since the PSK modulation format is widely applied in many wireless communications systems. On the other hand, it is known that the signal-preprocessing scheme at the electrical stage is effective in overcoming such nonlinearity-oriented obstacles. Indeed, injection of a narrow-angle (NA-) PSK signal into an MZM device with the DSB-SC configuration turns out to be the same as photodetection output in a binary-PSK (BPSK) modulation format, as demonstrated in our previous work.

In this paper, we report on our attempt to extend the performance of this advantageous method in order to deal with more sophisticated signal generation; we propose a method that enables one to generate a pair of dual-mode optical BPSK signals via an LN optical modulator with dual RF inputs and a carrier suppression feature. In conjunction with the appropriate bias setting, i.e., quadrature optical bias setting for two arms of the MZM device, this scheme leads to the generation of a quadrature-PSK (QPSK) signal at the stage of photodetection without causing fatal crosstalk. In comparison with the previously proposed method of QPSK signal generation where an NA-QPSK electrical signal is injected into a DSB-SC MZM device, one can expect less spectral broadening since the transient trajectories in the present scheme are less complicated and consequently lead to narrower bandwidths. This feature leads preferably to robust operations in bandwidth-limited systems. Thus, it is expected that our proposed QPSK modulation

---

Manuscript received December 2, 2002.
Manuscript revised February 10, 2003.

[†] The authors are with the Department of Electronic Engineering, The University of Tokyo, Tokyo, 113-8656 Japan.

[††] The authors are with New Technology Research Laboratory, Sumitomo Osaka Cement, Funabashi-shi, 274-8601 Japan.

a) E-mail: tsuchiya@ktl.t.u-tokyo.ac.jp

scheme, based only on a single optoelectronic device, provides the frequency-doubling functionality as well as the dispersion-tolerant-characteristics, which may lead to cost-effective implementation of advanced optical mm-wave transmitters at a central office in future fiber-optic picocell conflgurations.

2. Orthogonal Dual-Mode BPSK Signal Pair

Let an MZM device with a pair of RF inputs and carrier suppression functionality be considered here to explain the operation principle of the present scheme (Fig.1). The device can be either an optical single-sideband (SSB) modulator [5]-[7] or dual-electrode MZM device. The former consists of two MZM devices in parallel, and the latter is regarded as a parallel composite of two independent phase modulators. Such a device allows one to generate two dual-mode optical signals independently from a single optical carrier by injecting two driving electrical signals separately. Here, the elimination of the optical carrier component is advantageous for higher efficiencies in optical amplification and optical-to-electrical conversion processes as well as for suppression of the dispersion-induced power penalty in the case of phase modulators. This is possible by means of the DSB-SC operation of each integrated modulator in the former device, and an optical band rejection filter is additionally needed for the latter device. Here, a fiber Bragg grating (FBG) is probably suitable for the mm-wave application.

Let an optical carrier of frequency Ω be launched into two optical paths in the device and also phase-modulated individually through injection of an RF signal with frequency ω_i and NA-BPSK data of ϕ_i. Here, the subscript i identifies optical modulation in each optical path. Hereafter, we concentrate on the optical SSBM as a representative case. The DSB-SC modulation scheme for the SSBM device gives rise to the generation of upper and lower sidebands, as well as to the suppression of the carrier component, as mentioned above. The lower and upper sideband optical fields are expressed as $E_i \exp j\{(\Omega - \omega_i)t - \phi_i\}$ and E_i exp$j\{(\Omega + \omega_i)t + \phi_i\}$. Phasers of the dual-mode optical signals thuS generated are schematically drawn in Figs. 2(a) and (b).

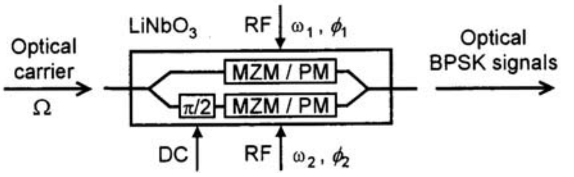

Fig. 1 Schematic of a LiNbO$_3$ modulator being considered; it should have double RF input ports and electrodes as well as the carrier suppression feature. One can use either the optical SSBM or dual-electrode MZM device. The former consists of two MZM devices in parallel and the latter contains two independent phase modulators (PM). The latter needs an external optical band elimination filter for carrier suppression.

If one sets the DC bias relationship to be quadrature, an optical phase difference of $\pi/2$ is introduced between these two optical signals. Here, the resultant electrical field at the optical modulator output is expressed as

$$\begin{aligned} E_{out} = {} & E_1 \exp j\{(\Omega - \omega_1)t - \phi_1\} \\ & + E_1 \exp j\{(\Omega + \omega_1)t + \phi_1\} \\ & + E_2 \exp j\{(\Omega - \omega_2)t - \phi_2 + \pi/2\} \\ & + E_2 \exp j\{(\Omega + \omega_2)t + \phi_2 + \pi/2\}. \qquad (1) \end{aligned}$$

The RF current ip generated at the photodetection stage is consequently given by

$$\begin{aligned} i_p \propto {} & 2E_1^2 \cos(2\omega_1 t + 2\phi_1) \\ & + 2E_2^2 \cos(2\omega_2 t + 2\phi_2) \\ & + 2E_1E_2 \cos\{(\omega_1 + \omega_2)t + \phi_1 + \phi_2 + \pi/2\} \\ & + 2E_1E_2 \cos\{(\omega_1 + \omega_2)t + \phi_1 + \phi_2 - \pi/2\} \\ = {} & 2E_1^2 \cos(2\omega_1 t + 2\phi_1) + 2E_2^2 \cos(2\omega_2 t + 2\phi_2). \\ & \qquad (2) \end{aligned}$$

Figures 2(c)-(e) indicate the I/Q diagrams of these signals at RF frequencies of ω_1 (c), $2\omega_2$ (d) and $\omega_1 + \omega_2$ (e), respectively, which correspond to the respective terms in the above equation. The RF phases $2\phi_1$ and ϕ_2 indicated in Figs.2(c) and (d) are given by the phase differences between two optical sidebands in Figs.2(a) and (b), respectively. RF phases of the two remaining terms are also indicated in Fig.2(e); one is the optical phase difference between the upper sideband in (b) and the lower sideband in (a), and the other is vice versa. Note that this relationship makes

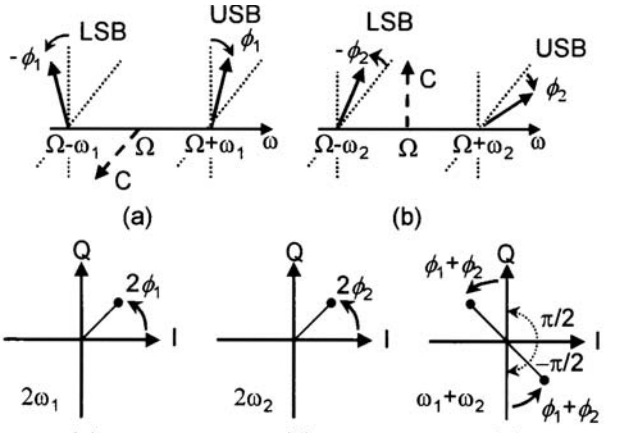

Fig.2 (a) and (b) Relative phase relationships of optical modes generated by an MZM device, which correspond to phase-modulated light with a $\pi/2$ phase difference. I/Q diagrams of RF signals generated by optical overlap of the optical modes and their photodetection, RF frequencies $2\omega_1$ (c), $2\omega_2$ (d) and $\omega_1 + \omega_2$ (e), USB: upper sideband, LSB: lower sideband, C: carrier.

the $\omega_1 + \omega_2$ terms vanish, which provides the orthogonal relationship between the two photodetected outputs and prevents crosstalk problems.

Here, we assume a situation where this operation scheme is applied to the generation of a photodetected signal in the QPSK modulation format. We provide the following condition so as to inject a set of the input electrical signals shown in Figs.3(a) and (b) into the MZM device: $E_1 = E_2$, $\omega_1 = \omega_2$, $\phi_1 = m\pi/4$ and $\phi_2 = n\pi/4 + \pi/4$. Here, m and n denote indices of binary phase shifts (± 1) for the injected NA-BPSK signals. The phase difference of $\pi/4$ between the injected NA-BPSK signals gives rise to the orthogonal phase relationship, the second orthogonality, between the photodetected BPSK signals. Thus, the quadrature BPSK signal, that is, a QPSK signal, is generated at the frequency of $2\omega_1$; consequently,

$$i_p \propto 2E_1^2\{\cos(2\omega_1 t + m\pi/2) + \sin(2\omega_1 t + n\pi/2)\}. \tag{3}$$

Here, one should note that the transient trajectories of the present QPSK signal are more similar to the ideal ones than those in the case of NA-QPSK signal injection, which suggests some superiority of this method over the previous one in terms of the bandwidth.

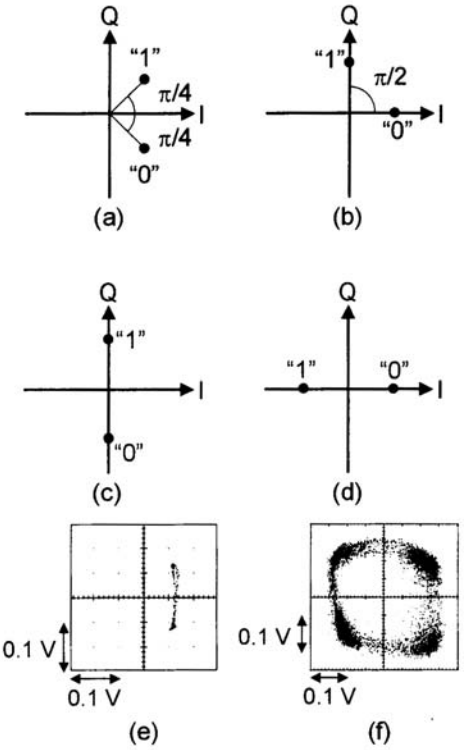

Fig.3 I/Q diagrarns are shown for one original NA-BPSK signal (a) and the other NA-BPSK signal, whose phase difference is $\pi/4$ (b). Photodetected BPSK signals corresponding to (a) and (b) are shown in (c) and (d), respectively. The measured 30 GHz NA-BPSK signal injected into one of the optical SSB modulator inputs (e) and the 60 GHz QPSK signal at the PD output with electrical amplification (f).

In the final part of this subsection, we describe subcarrier multiplexing (SCM) where the parameters are set as follows: $\omega_1 \neq \omega_2$, $\phi_1 = m\pi/4$ and $\phi_2 = n\pi/4$. Here, the photocurrent is given by

$$i_p \propto 2E_1^2 \cos(2\omega_1 t + m\pi/2) + 2E_2^2 \cos(2\omega_2 t + n\pi/2). \tag{4}$$

It should be noted here that, in this SCM method, one can avoid such nonlinearity-oriented problems as (a) intermodulation distortion and (b) generation of unnecessary frequency components at $\omega_1 + \omega_2$, which are, in general, caused by electrical addition of two NA-BPSK signals prior to their injection into a DSB-SC MZM device. Such optical addition prevents the former problem because two independent RF signals are fed into two integrated modulators separately. The latter is overcome by setting the orthogonal phase relationship between the two optical paths, as long as no additional phase shift is added during fiber-optic transmission.

3. Experiments

In order to confirm the operation principle of the present scheme, we performed 60 GHz experiments in which an electrical (photodetected) QPSK signal was generated by means of the above-mentioned method. The configurations employed for the experiments are shown in Figs.4; we applied the scheme to two kinds of LN modulators: an x-cut optical SSBM device [8] (Fig.4(a)) and a dual-electrode MZM device combined with an FBG band elimination filter (Fig.4(b)).

In Fig.5, the experimental setup used for the demonstration is shown. To generate a set of BPSK

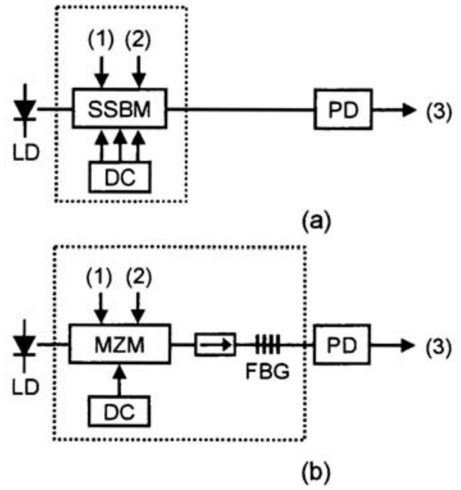

Fig.4 Configurations for QPSK signal generation. While an optical SSBM device is used in (a), a dual-electrode Mach-Zehnder interferometer modulator is combined with a fiber Bragg grating in (b). The input and output signals (1), (2) and (3) correspond to I/Q diagrams (a), (b), and an overlap of (c) and (d) in Figs. 3, respectively.

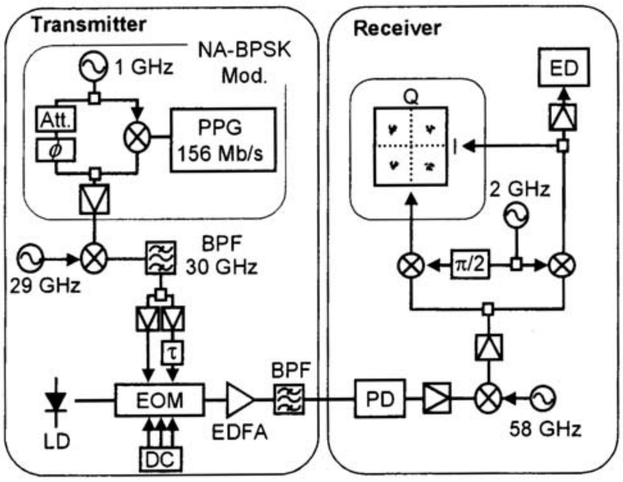

Fig.5 Experimental setup for QPSK signal generation through the generation of orthogonal dual-mode optical BPSK signals with an LN optical modulator. EOM in the lower left indicates an electrooptic modulation scheme with dual RF inputs and carrier suppression feature. One candidate device for the scheme is an optical SSBM device and another is a dual-electrode MZM device. In the latter case, a fiber Bragg grating is used for elimination of the optical carrier component.

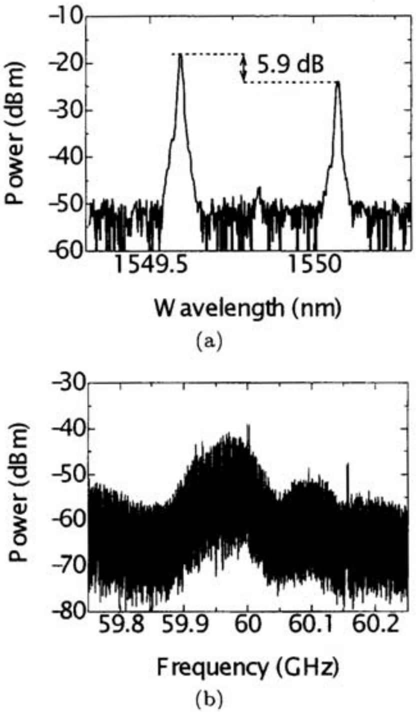

Fig.6 Dual-mode optical signal generated by the present method with an optical SSBM device (a). RF spectrum of 60 GHz QPSK signal measured at the electrical amplifier output after photodetection (b).

signals to be injected into the optical modulator, we prepared an NA-BPSK modulated electrical signal, divided it into two, and delayed one of these two by a quarter-wave. This was merely for the sake of simplicity, and two independent NA-BPSK signals should be injected in an actual case. The original NA-BPSK signal was generated with an attenuator and a phase shifter, as shown in the upper left of Fig.5, which was measured as the I/Q trace shown in Fig.3(e). Light emitted from a distributed feedback laser diode was led into the LN modulator, modulated by the above-mentioned electrical signals, and subsequently amplified through an Er-doped fiber amplifier (EDFA). An optical band-pass filter was set at the output of the EDFA in order to suppress its amplified spontaneous emission noise.

Figure 6(a) shows optical spectra measured for optical mm-wave signals generated with the optical SSBM device. One should note that there exists a difference in the spectral power values between the two peaks. This originates from the difference in the phase relationship between individual BPSK components in each sideband spectrum and can be explained quantitatively as follows. If one takes into consideration the phase differences of $\pi/2$ in the optical domain and $\pi/4$ in the RF domain, the optical modal power difference should be given by

$$20 \times \log\left\{\cos\left(\frac{\pi/2+\pi/4}{2}\right)\Big/\cos\left(\frac{\pi/2-\pi/4}{2}\right)\right\}$$
$$= 7.6\ [\mathrm{dB}]$$

for the case of single tone signal injection. Since the 5.9dB difference corresponds to a 7.2 dB power difference in the case of single tone signal injection, which has been experimentally confirmed, a fairly good agreement is thus obtained. Consequently, a QPSK signal of the 60 GHz band was successfully generated at the photodetection stage; Fig.3(f) shows a clear I/Q diagram of the QPSK signal thus obtained. This experimental result confirms the our proposed operation principle.

Figure 6(b) shows the RF spectrum measured around 60 GHz. The RF carrier component was apparently suppressed. On the other hand, there exists a periodic distortion in the spectrum, which is probably due to the residual interference between the two BPSK signals. This is because the origin of the two signals is the same in this particular experiment and the modulator therefore acts as a Mach-Zehnder filter. Indeed, the spectral period is approximately 150 MHz, which coincides with the inverse of the time difference between two input signals. If the two signals are independent of each other, which is more realistic, the spectral distortion may disappear.

Furthermore, we performed a similar experiment with a dual-electrode MZM device with an FBG band elimination optical filter. The inset of Fig.7 shows the measured I/Q diagram, which suggests that the scheme works well also with the second device. The result of bit-error-rate (BER) measurement (156Mbps) performed for a demodulated mm-wave signal is indicated in Fig.7. While a separate measurement indicates a clear eye opening for the signal, BER of $< 10^{-9}$ an

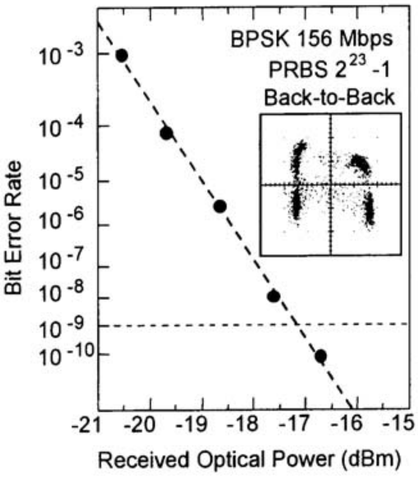

Fig.7 BER characteristics of the present scheme for signal generation and photodetection. The BPSK bit rate was 156 Mbps. The inset shows an I/Q diagram of the signal.

error-free operation in other words, was achieved at the received optical power of −17dBm. However, it was found that there exists an asymmetric feature in the I/Q diagram in Fig.7. This is probably due to imbalance in the Vπ/ voltages of two phase modulators.

4. Conclusion

A novel LN modulation technique for synthesizing a pair of dual-mode optical BPSK signals in an orthogonal phase relationship has been proposed for crosstalk-free generation of photodetected quadrature PSK signals at the receiver of a fiber optic mm-wave link. With a single LN modulator having dual RF inputs and carrier suppression together with the quadrature bias, i.e., a $\pi/2$ phase offset between two optical paths, two BPSK signals have been generated and merged without causing nonlinearity-oriented problems at the photodetection stage. We pointed out that this modulation scheme is beneficial for QPSK signal generation because of a reduction of unnecessary bandwidth broadening caused by sophisticated transient trajectories in the previously. proposed method. The operation principle has been confirmed in preliminary experiments for 60-GHz-band signals both with an optical SSBM device and with a dual-electrode MZM device.

Acknowledgments

The authors would like to thank M. Izutsu of Communications Research Laboratory for his encouragement and support. This work is partly supported by a JST-CREST program. The authors appreciate Ms. S. Ikeya for her cordial support.

References

[1] H. Ogawa, D. Polifko, and S. Banba, "Millimeter-wave fiber optics systems for personal radio communication," IEEE Trans. Microw. Theory & Tech., vol.40, no.12, pp.2285–2993, 1992.

[2] H. Ogawa, "Microwave and millimeter-wave fiber optic technologies for subcarrier transmission systems," IEICE Trans. Commun., vol.E76–B, no.9, pp.1078–1090, Sept. 1993.

[3] J.J. O'Reilly, P.M. Lane, R. Heidemann, and R. Hofstetter, "Optical generation of very narrow linewidth millimetre wave signals," Electron. Lett., vol.28, no.25, pp.2309–2311, 1992.

[4] J.J. O'Reilly and P.lvl. Lane, "Fiber-supported optical gener -ation and delivery of 60 GHz signals," Electron. Lett., vol.30, no.16, pp.1329–1330, 1994.

[5] M. Izutsu, S. Shikama, and T. Sueta, "Integrated optical SSB modulator/frequency shifter," IEEE J. Quantum Electron., vol.QE-17, no.11, pp.2225–2227, 1981.

[6] S. Shhnotsu, S. Oikawa, T. Saitou, N. Mitsugi, K. Kubodera, T. Kawanishi, and lvl. Izutsu, "Single side-band modulation performance of a $LiNbO_3$ integrated modulator consisting of four-phase modulator waveguides," IEEE Photonics Tech. Lett., vol.13, no.4, pp.364–366, 2001.

[7] S. Shimotsu, S. Oikawa, T. Saitou, N. Mitsugi, K. Kubodera, T. Kawanishi, and M. Izutsu, "Optical single-sideband modulator," Proc. OFC 2000, pp.214–217, Baltimore, USA, 2000.

[8] K. Higuma, Y. Hashimoto, M. Yatsuki, and H. Nagata, "Electrode design to suppress thermal drift in lithium niniobate modulators," Electron. Lett., vol.36, no.24, pp.2013–2014, 2000.

Shinji Nakadai was born in Chiba, Japan, in 1978. He received the B.E. and M.E. degrees in electronic engineering from the University of Tokyo in 2001 and 2003, respectively. This work was done while he was a master course student in the same department engaged in research studies on millimeter-wave photonics. Presently, he is with NEC Corporation.

Kaoru Higuma received his B.S. degree in physics and M.E. degree in applied optics from Waseda University, Tokyo, Japan, in 1994 and 1996, respectively. In 1996, he joined Sumitomo Osaka Cement Co., where he has been engaged in the research and development of optical $LiNbO_3$ modulators.

Satoshi Oikawa received his B.E. and M.E. degrees in electrical engineering from Nihon University, Tokyo, Japan, in 1991 and 1993, respectively. In 1993, he joined Optoelectronics Research Division, New Technology Research Laboratories, Sumitomo Osaka Cement Co., Ltd., Chiba, Japan. He has been engaged in the research and development of optical modulators.

Masato Kishi was born in Tokyo, Japan. He received his B.S. and M.S. degrees in physics from Nihon University in 1973 and 1975, respectively. From 1975 to 1990, he was with the Institute of Interdisciplinary Research and the Research Center for Advanced Science and Technology, which belonged and belongs to the University of Tokyo, respectively. In 1990, he moved to the Department of Electronic Engineering in the same university. He has been involved in many research projects in the fields of semiconductor material science and technology as well as in the laboratory education curriculums of the department. His current research interests are in advanced characterization techniques for Si and optoelectronic materials with emphasis on microscopic Raman spectroscopy and nonlinear optics/optoelectronics.

Masahiro Tsuchiya was born in Shizuoka, Japan, on September 28, 1960. He received his B.E., M.E., and Ph.D. degrees from the University of Tokyo, Japan, in 1983, 1985, and 1988, respectively, all in electronic engineering. His doctoral dissertation concerned the resonant tunneling phenomena in ultrathin semiconductor heterostructures and related devices. He was a post-doctoral fellow with the University of California at Santa Barbara from 1988 to 1990, and a research staff member of the Research Development Corporation of Japan from 1990 to 1991, where he was engaged in research on semiconductor microstructures with quantum effects and their applications to electronic and optical devices. In 1991, he joined the Department of Electronic Engineering, the University of Tokyo as a lecturer, and became an associate professor in the same department in 1993. In 1996, he spent his sabbatical year as a visiting researcher at Bell Laboratories, AT&T/Lucent Technologies, Holmdel, NJ. His current research interests are ultrashort pulse generation, optical probing techniques for high-frequency circuit analyses, semiconductor-related optical nonlinearity and its applications, microwave and millimeter-wave photonic devices and links, advanced optoelectronic material characterization techniques, and implementations of practical systems with those devices and phenomena incorporated. Dr. Tsuchiya is a member of the Japan Society of Applied Physics and also belongs to IEEE LEOS.